POSSIBLE METHODS FOR BIODYNAMIC FEEDTHROUGH COMPENSATION IN BACKHOE OPERATION

Heather C. HUMPHREYS[1] and Wayne J. BOOK[2]
Georgia Institute of Technology
Mechanical Engineering
Atlanta, GA 30318
USA
Email: heather.humphreys@gatech.edu, wayne.book@me.gatech.edu

This research presents an investigation on the effects of biodynamic feedthrough on an advanced backhoe control system. This previously developed backhoe user interface uses coordinated position control with haptic feedback and is used as a testbed for this research. Results indicate that the coordinated control provides more intuitive operation that is easy to learn, and the haptic feedback relays meaningful information back to the user in the form of force signals from digging forces and system limitations. However, they also show that the current system has significant problems with biodynamic feedthrough. Biodynamic feedthrough refers to the phenomenon where the motion of the controlled device excites motion of the operator, resulting in undesirable forces applied to the input device and control performance degradation. According to the literature, and to industry backhoe and excavator interface designers, this is also a significant problem in state-of-the-art user interfaces. This work presents simulation studies on several possible methods for biodynamic feedthrough compensation.

Keywords: biodynamic feedthrough, control, operator interface, machine dynamics

1 INTRODUCTION

In some operator-controlled machines, motion of the controlled machine excites motion of the human operator, which is fed back into the control device, causing unwanted input and sometimes instability; this phenomenon is termed biodynamic feedthrough. In operation of backhoes and excavators, biodynamic feedthrough causes control performance degradation. This work utilizes a previously developed advanced backhoe user interface which uses coordinated position control with haptic feedback, using a SensAble Omni six degree-of-freedom haptic display device. Initial human factors testing revealed significant problems with biodynamic feedthrough, resulting in undesirable oscillations in output. This paper presents several possible methods of compensation for biodynamic feedthrough, as well as simulation results. Further simulations and human factors testing are currently in progress.

2 BACKGROUND

Relevant previous work can be divided into three main sections. The first includes the development of the Haptically Enhanced Robotic Excavator (HEnRE) testbed, the second involves

[1] Heather C. Humphreys, mechanical engineering PhD student and NSF/NDSEG fellow
[2] Wayne J. Book, HUSCO/Ramirez Distinguished Professor of Fluid Power and Motion Control

biodynamic feedthrough in a range of applications, and the third involves the modelling of biodynamic feedthrough in the HEnRE system.

2.1 Haptically Enhanced Robotic Excavator (HEnRE)

An advanced user interface for a backhoe has been developed, called the Haptically Enhanced Robotic Excavator (HEnRE), which uses coordinated position control with haptic feedback. The HEnRE system is described in **Kontz, M.E.** (2007), **Frankel, J.G.** (2007) and **Kontz, M.E.; Book, W. J.** (2006). The HEnRE system uses a SensAble Omni™ six degree-of-freedom (DOF) haptic display input device, shown in Figure 1.

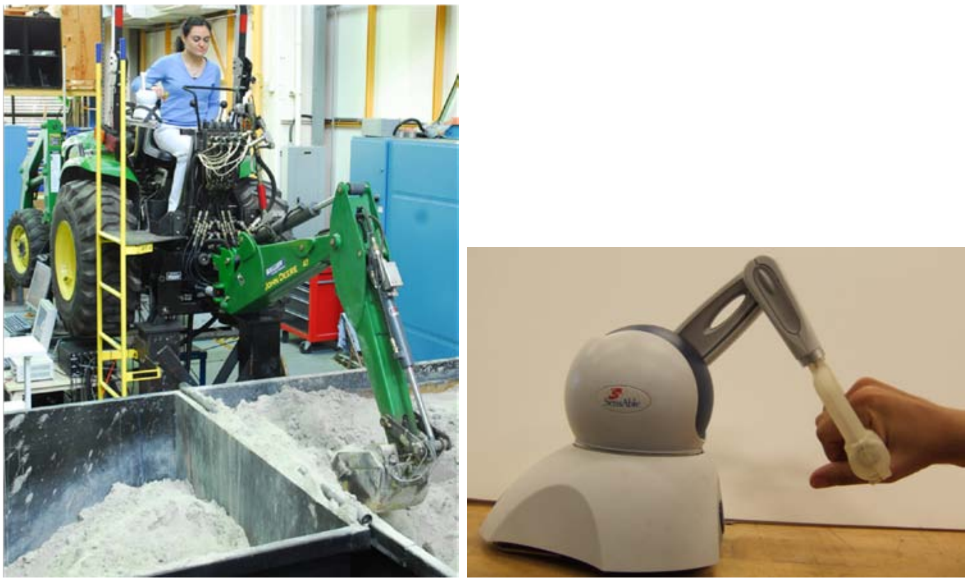


Fig. 1: HEnRE testbed and SensAble Omni 6-DOF input device

The Omni is mounted beside the tractor seat. It enables coordinated position-to-position mapping from the input device to the bucket position, allowing the use of a computer for the inverse kinematics calculations. In contrast, state-of-the-art backhoe user interfaces use position-to-velocity mapping with four independent inputs to control four actuators.

2.2 Biodynamic Feedthrough

Biodynamic feedthrough is a significant problem in control of mobile hydraulic equipment, though it has received little attention by researchers in this area. However, it has been a widely recognized and studied problem in the area of high-performance aircraft for several decades.

An in-depth study on biodynamic feedthrough was performed by Systems Technology, Inc., under a contract for the US Air Force **Allen, R.W.; H.R. Jex; R.E. Magdaleno** (1973) and **Jex, H.R. and R.E. Magdaleno** (1978). It focuses on development of lumped-parameter biomechanical models for the human pilot, for the purpose of developing software to simulate the interaction between human body dynamics and structural modes in manual control systems. The publications do not present detailed human body models for fore-aft motion. In general, results indicate that biodynamic feedthrough effects are primarily of involuntary nature; any cognitive or neuro-muscular compensation is negligible.

Some studies on biodynamic feedthrough do consider hydraulic equipment applications. In **Arai, F.; J. Tateishi; T. Fukuda** (2000), a similar investigation on biodynamic feedthrough in excavator operation is performed using simplified mass-spring-damper models, though the experimental validation is limited. Another similar simulation-only investigation is presented in **Margolis, D.; T. Shim** (2003).

2.3 Modeling of Biodynamic Feedthrough in HEnRE

The first step in compensator design was to model the HEnRE system including the biodynamic feedthrough. Because these compensators are applied and tested with this particular hardware system, it is important that the models match well with measured data. The HEnRE system was modelled as a lumped parameter system using a hybrid of first principles and system identification.

As a first step, in order to reduce the model complexity, only one degree of freedom was considered. The stick joint is controlled using the z-axis (fore-aft axis) of the Omni. By positioning the backhoe in an appropriate configuration and assuming small angle approximation, motion is produced primarily in the fore-aft direction.

The modelling of the HEnRE system is described in detail in **Humphreys, H.; W. Book** (2009). The system was divided into three main dynamic components: 1) the stick valve and cylinder, 2) the tractor and cab structure, and 3) the human body biomechanics. The input device dynamics are negligible. Following are the transfer functions for each of these components.

Equation (1) is a model for the response of the stick valve and cylinder. The input is the valve control signal U(s), and the output is the cylinder position Y(s). The cylinder has a position sensor, so both of these signals can be measured in the hardware.

$$\frac{Y(s)}{U(s)} = \frac{K_{VC}}{s} \cdot \frac{\omega_{nVC}^2}{\left(s^2 + 2\zeta_{VC}\omega_{nVC}s + \omega_{nVC}^2\right)} \tag{1}$$

Equation (2) is a model for the structural dynamics of the tractor and backhoe. For this study, the signals of interest are the input cylinder position Y(s), and the output cab position C(s). In the hardware testing, the cab acceleration is measured, so the second derivative of C(s) is used; in testing, the models are modified accordingly.

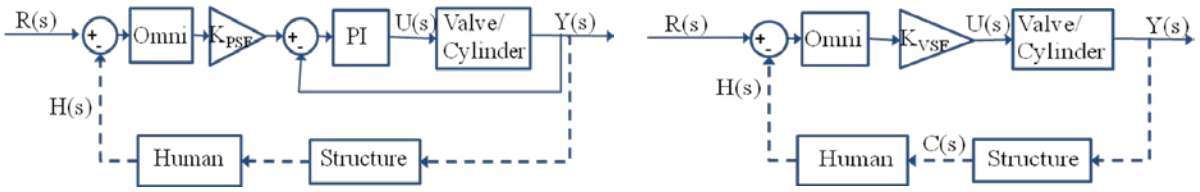
$$\frac{C(s)}{Y(s)} = \frac{K_s\left(2\zeta_{s1}\omega_{sn1}s + \omega_{sn1}^2\right)}{\left(s^2 + 2\zeta_{s1}\omega_{sn1}s + \omega_{sn1}^2\right)} \cdot \frac{\left(2\zeta_{s2}\omega_{sn2}s + \omega_{sn2}^2\right)}{\left(s^2 + 2\zeta_{s2}\omega_{sn2}s + \omega_{sn2}^2\right)} \tag{2}$$

Equation (3) is a model for the vibration of the human body induced by the cab motion. The signals of interest are the input cab motion C(s) (or acceleration s^2*C(s)), and the human operator's induced hand motion H(s).

$$\frac{H(s)}{C(s)} = \frac{K_H\left(s + z_{1H}\right)^2}{\left(s + p_{1H}\right)^2} \tag{3}$$

Data for this human biodynamic feedthrough were obtained by two methods: human subject testing and human body dynamic modelling software LifeMOD™. In both cases, the seat was externally excited, and the resulting hand motion was measured.

Control configurations for both position control and rate control have been investigated. Position control has been the primary method, since it has advantages for haptic feedback. Figure 2 shows block diagrams for both position control and rate control, where R(s) indicates the reference, or intentional command input. In both cases R(s) is the intentional hand motion, and H(s) is the unwanted hand motion.



Position Control with PI Controller

Rate Control

Fig. 2: Block diagrams for position control and rate control

The dashed lines indicate the biodynamic feedthrough loop. The system response without biodynamic feedthrough, or with the operator using the input device remotely, is given by these block diagrams minus the dashed loop. In some subsequent analyses, "without biodynamic feedthrough" indicates that the sections of the block diagrams connected by dashed lines are omitted.

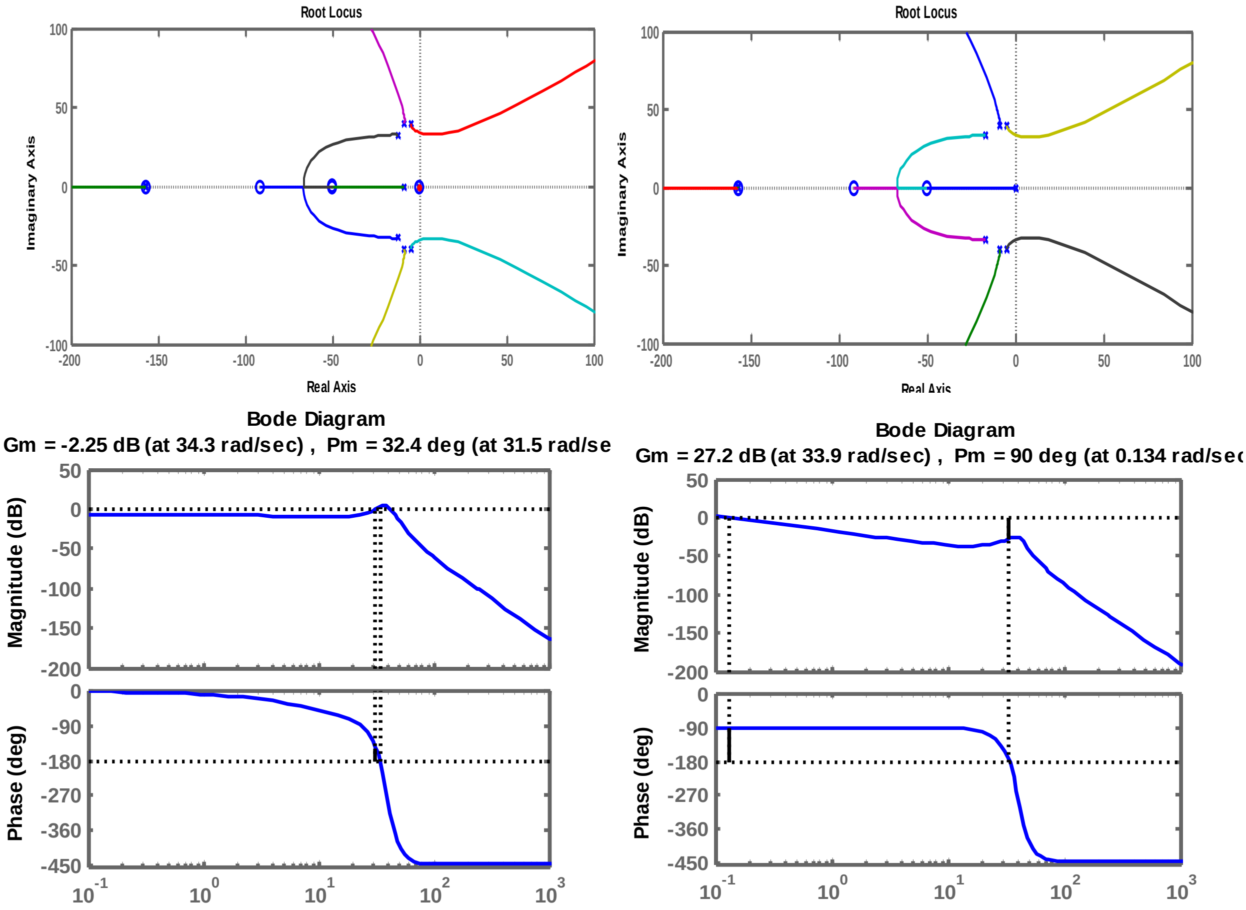
3 OVERVIEW OF POSSIBLE COMPENSATION METHODS

A number of possibilities for controller design to minimize the adverse effects of biodynamic feedthrough have been considered, and several simple modifications have shown promising results in simulation. So far, only nominal parameters have been considered, but robustness is an important factor in the final compensator design.

3.1 Compensation design objectives

In general, satisfactory control performance can be achieved easily for the remote operation case, without biodynamic feedthrough. The first objective is to minimize the effect of biodynamic feedthrough on the system response; in other words, to make the system response with biodynamic feedthrough more closely match the response without biodynamic feedthrough.

Figure 3 shows root locus plots for both the position controlled and velocity controlled systems, with respect to the gains denoted as K_{PSF} and K_{VSF} in Figure 2. Note the set of three lightly damped flexible poles, one of which moves toward instability with increasing gain. Two of these lightly damped poles result from the biodynamic feedthrough; without the biodynamic feedthrough loop, only the leftmost of the set of lightly damped poles would appear.



Position Control with PI Controller   Rate Control

Fig. 3: Root locus plots with biodynamic feedthrough (top); Bode plots for the system with biodynamic feedthrough and nominal gains (bottom)

Both root locus plots look very similar; however, much higher gains are needed to approach instability with position control than velocity control. In fact, in the nominal case, the position controlled model is unstable. The hardware system does not appear to be unstable, but it does exhibit substantial oscillations and limit cycling. This discrepancy results from linearization of the models; limit cycles would not appear in these linear models. The same modifications which stabilize the linear model are expected to similarly improve system response in the nonlinear system. Simulations show that even very small changes in the locations of the flexible poles can significantly impact the system response. Figure 3 also shows Bode plots of the nominal system for position control and rate control. Again, they show that the position controlled case is unstable with the nominal gain.

3.2 Overview of possible approaches

Several approaches to this problem have been considered. First, a few simple classical methods were investigated, including 1) varying the gain on the input device, K_{PSF} and 2) adding a notch filter at the frequency of the lightly damped poles. Advantages and disadvantages of these will be discussed. Next, a state space approach to minimize cab acceleration is considered, which is the focus of current efforts. Finally, a few more advanced and robust adaptive techniques are discussed.

4 CLASSICAL COMPENSATION DESIGN

Two modifications are discussed: scaling, or varying the input device gain, and addition of a notch filter.

4.1 Scaling

In the position control case, the gain K_{PSF} refers to the scaling between the input device/human hand position and the backhoe position. Decreasing this gain corresponds to increasing the input device workspace, which improves stability with biodynamic feedthrough and can significantly improve system response. By varying the input device workspace size, we can effectively vary the relative magnitudes of the intended hand motion input R(s) and the undesirable hand motion resulting from the biodynamic feedthrough H(s). However, significant modifications to this workspace size require hardware changes and are limited by ergonomic factors. Figure 4 shows the unstable response with biodynamic feedthrough for the nominal case, as well as the system response corresponding to a doubled Omni workspace size.

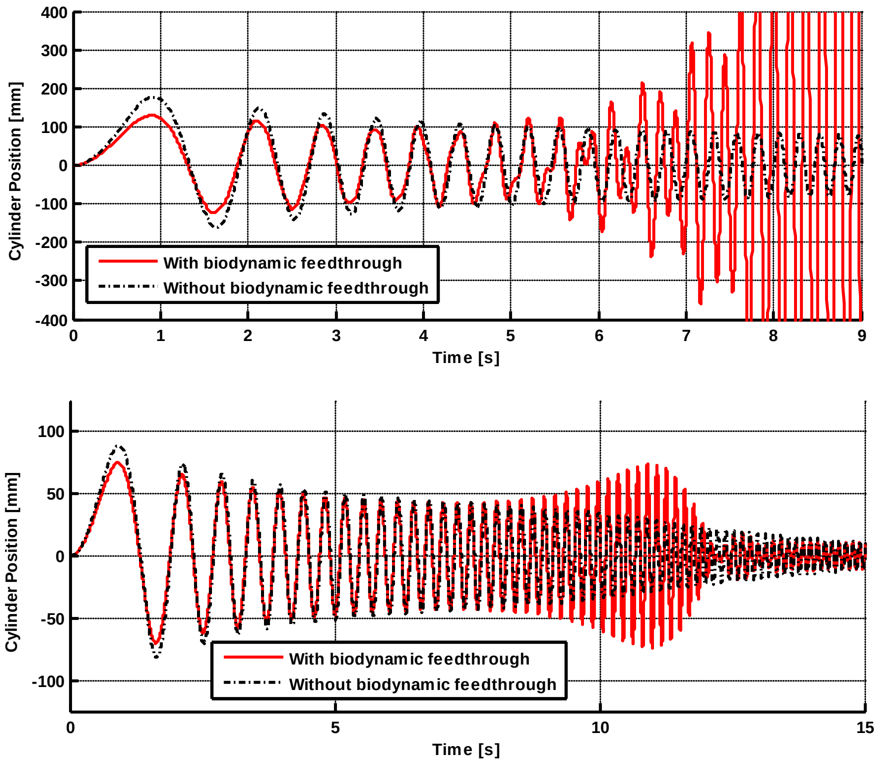


Fig. 4: Cylinder position response to chirp sine input for nominal Omni workspace size (top) and doubled Omni workspace size (bottom)

Figure 5 shows the amplitude ratio versus frequency, comparing response with biodynamic feedthrough to response without biodynamic feedthrough, for a range of further reduced K_{PSF} values. This amplitude ratio for K_{PSF}=0.055 is a comparison of the amplitudes from Figure 4.

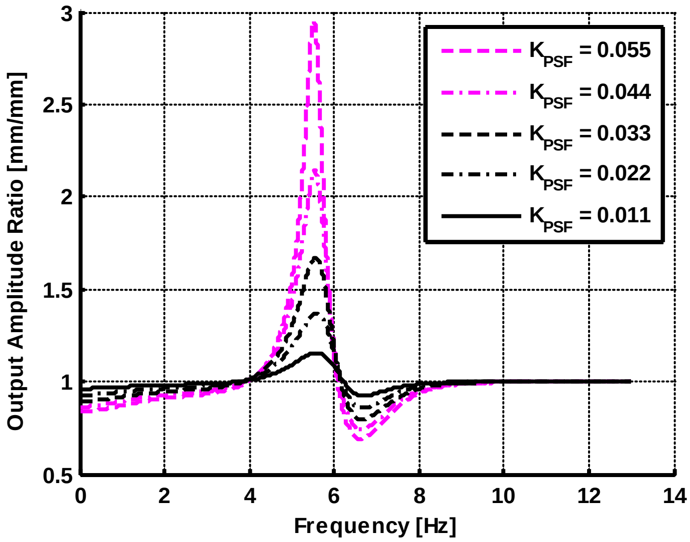


Fig. 5: Amplitude ratio versus frequency, comparing response with biodynamic feedthrough to response without biodynamic feedthrough, for a range of K_{PSF} values

Comparing this result to the root locus plot shown in Figure 3, the plot for K_{PSF}=0.011 corresponds to very low gain. The amplitude ratio for K_{PSF}=0.011 stays close to unity for all frequencies, although the root locus plot shows that the set of six flexible poles are still lightly damped. This indicates that small changes in those lightly damped pole locations can cause significant improvements in system performance. However, the amplitude ratio K_{PSF}=0.011 also corresponds to an increase in the input device workspace size by a factor of 10, which is not feasible in practice. Varying this gain may be sufficient to stabilize the system, but further improvement is needed.

4.2 Filtering

Next, simulations were tested using a notch filter near the frequency of the set of flexible poles. The filter is located in the feedforward loop with the input device. The transfer function for the notch filter is given in Equation (4). It includes two zeros placed near the flexible poles, as well as two real poles.

$$D_{NOTCH} = \frac{s^2 + 2\varsigma_N \omega_N + \omega_N^2}{(s+\omega_N)^2} \tag{4}$$

Figure 6 shows Bode diagrams for the system with and without the added notch filter. Notice the increase in system damping.

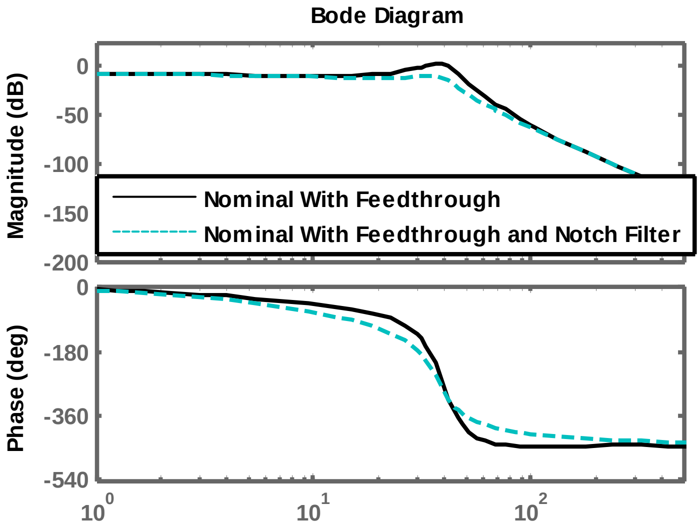


Fig. 6: Comparison of Bode diagrams with and without added notch filter, for position control with biodynamic feedthrough

Figure 7 shows the filtered system responses to a chirp sine input, with nominal gain. The effect of the biodynamic feedthrough is significantly diminished.

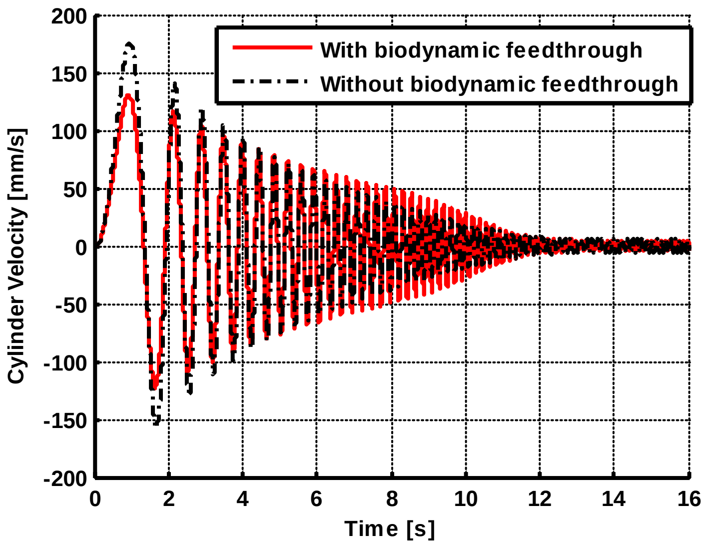


Fig. 7: Time response to chirp sine input for position controlled system with notch filter

While this filtering approach works well in simulation, it is not robust to parameter variations in the system model. For successful hardware implementation, some form of adaptive filtering would likely be necessary. Also, the filtering must be limited, since the filter is in the operating frequency range and also affects the desired command input.

5 STATE SPACE COMPENSATION DESIGN

A state space approach, which is the focus of current efforts, utilizes the measurement of cab acceleration to minimize cab acceleration. This measurement is useful in compensating for modelling inaccuracies and parameter variations. The goal of the observer/controller is to drive the cylinder position to the reference, while minimizing cab acceleration, which subsequently reduces the unwanted motion of the human hand. Weights for the two outputs can be selected in the controller design, so that the controller achieves an appropriate balance between tracking the desired cylinder position and minimizing cab acceleration. A variety of state space control configurations are possible. A block diagram for the proposed state space approach is shown in Figure 8.

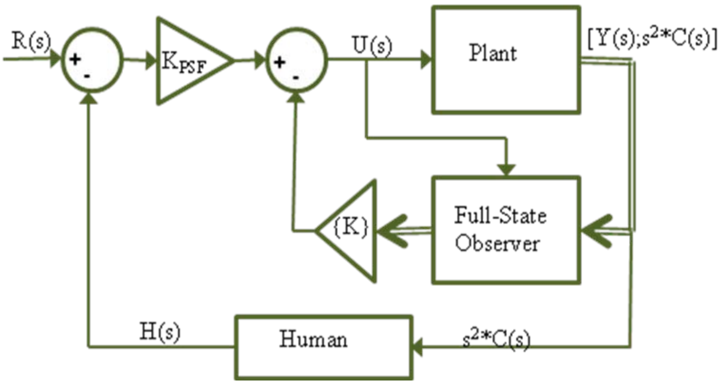


Fig. 8: State space system model

In this configuration, the state space plant includes both the valve/cylinder dynamics and the tractor/cab structural dynamics. The human model is included as a separate block, since no measurement information is available for the human. Preliminary simulations with a slightly simplified plant model indicate that good tracking can be achieved and cab acceleration can be significantly reduced with this full-state feedback configuration. Closed loop pole locations were selected using the symmetric root locus technique. In this configuration, the closed loop state space system is inside the biodynamic feedthrough loop, acting as a plant for that closed loop system. Because of mechanical and ergonomic limitations, large variations in K_{PSF} are unlikely; therefore, the poles of the full state feedback system can be selected such that the outer feedback loop produces desirable response.

The major advantage of this approach is that it utilizes the cab acceleration measurement, rather than just the model, to minimize structural vibration and subsequently human body vibration. However, achieving sufficient robustness may still be an issue.

6 OTHER POSSIBLE COMPENSATION TECHNIQUES

Several other compensation techniques have also been considered, although they have not been implemented in simulation. Initially, the dynamics of the SensAble Omni input device were neglected. However, the Omni has the capability to display haptic forces, which could be used to oppose the undesirable hand motion. Simulations indicate that the damping force display could also be used to oppose the unwanted hand motion and mitigate the biodynamic feedthrough effects. However, this approach is also limited by ergonomic factors.

Another possible approach is the use of an adaptive filter. The notch filtering technique described previously produced promising results in simulation. The major limitation of that approach is its susceptibility to parameter variations and modelling inaccuracies. If the center frequency of the filter can be adapted based on the cab acceleration measurement, then that susceptibility could be reduced.

7 CONCLUSIONS AND FUTURE WORK

This paper presents some preliminary studies on possible compensation methods for biodynamic feedthrough. Further investigation on robustness to model variations is needed. Simulation studies using the state space compensation design method described earlier are in progress. Hardware implementation and setup for human subject testing are also in progress. The human subject tests involve tracking experiments performed in two configurations: 1) with the operator in the standard seated position on the tractor, and 2) with the operator using the input device remotely. The tracking signal and cylinder position/velocity are displayed on a monitor in both cases.

8 LIST OF NOTATIONS

R	Reference hand position	mm
U	Control input to valve	V
Y	Cylinder position	mm
H	Undesirable hand motion (position), resulting from biodynamic feedthrough	mm
C	Cab position	mm
K_{PSF}	Position scale factor gain	---
K_{VSF}	Velocity scale factor gain	---
K_H	Gain for hand transfer function	---
K_S	Gain for structure transfer function	---
K_{VC}	Gain for valve/cylinder transfer function	---
K	Controller gain vector	---
ω	Natural frequency	rad/s
ς	Damping ratio	N-s/m

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